The Ionisation produced by an α-Particle. Part II.—*Connection between Ionisation and Absorption.*

By H. Geiger, Ph.D.

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In the course of some experiments described in a previous paper,* the ionisation produced by an α-particle along its path in air (Bragg curve) was determined with Radium C as source, and under conditions which were most favourable for saturation. The general shape of this curve is well known. The ionisation due to a parallel pencil of α-particles from Radium C (range in air, 7·06 cm.) increases up to a maximum value at 6·5 cm. During the next 5 mm. of its path the ionisation decreases rapidly to zero.

The following experiments were undertaken to throw light on the law of absorption of the α-particle, and to establish, if possible, a connection between its velocity and ionising power.

I. *The Retardation of the α-Particles in passing through Matter.*

In 1906, Prof. Rutherford† by a photographic method succeeded in measuring the magnetic deflection of the α-particles, and was able to determine the relative velocity at different points of the path by interposing different numbers of aluminium sheets of known stopping power. The extremely weak impressions which the α-particles produce on a photographic plate when near the end of their path made a determination of the velocity at this point very difficult. The velocity which Prof. Rutherford obtained for 14 aluminium sheets, equivalent in stopping power to nearly 7 cm. of air, was still 0·43 of the initial velocity. This somewhat surprising result has led to various speculations as to what actually happens to an α-particle at the end of its path. It has been assumed that either the α-particle loses its charge at the end of the range, or that it is stopped there abruptly.

The experimental difficulties of the magnetic deflection of the α-particles are appreciably less to-day than formerly. The greater amount of radium available allows us to use an intense source of α-particles, and the scintillation method for the observation of the deflected α-particles recently developed by many observers is more satisfactory than the photographic method. In the light of these advantages Prof. Rutherford suggested that a redetermination of the velocity of an α-particle along its path was desirable.

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* 'Roy. Soc. Proc.,' A, vol. 82, p. 486, 1909.

† 'Phil. Mag.,' vol. 12, p. 138.

An accurate determination of the magnetic deflection will only be possible if the pencil of α-particles passing through the magnetic field is narrow and well defined. For this reason the active deposit from radium emanation was concentrated on a thin wire of only 0·12 mm. diameter. By means of a small spring arrangement this wire (A in fig. 1) was stretched in a horizontal position parallel to the lines of force of the magnetic field between M and N and parallel also to a fine slit B of less than 0·1 mm. width. This slit and the spring were fixed to a slide, which fitted into the wider part of the brass case KRSR′K′, the slide being introduced and removed through the ground glass stopper P. The length of the wire was 1 cm., and its distance from the slit 7·2 cm. The cylindrical pole-pieces had a diameter of 7 cm. and were 0·9 cm. apart. With a good vacuum the α-particles expelled from the active surface of the wire travelled through the magnetic field as a well-defined beam and produced a very narrow, horizontal line of scintillations on the zinc sulphide screen S. A microscope suitable for observing the scintillations could be moved vertically parallel to the screen by means of a screw and its position read on a scale to 1/20 of a millimetre. The eye-piece of the microscope was fitted with a horizontal wire which was just thick enough to be visible against the slightly illuminated zinc sulphide screen. It was easy to adjust the wire repeatedly on the line of scintillations within a tenth of a millimetre, at least as long as the range of the α-particles was not too much diminished by the sheets of mica which had been interposed.

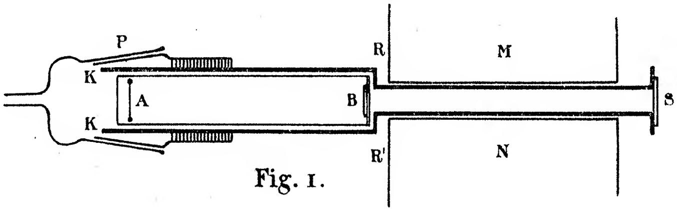

Fig. 1.

An experiment was carried out in the following way. The active wire was fixed exactly parallel to the slit and then brought into the brass case in the position shown in fig. 1. The apparatus was then exhausted and kept in continuous connection with a charcoal bulb dipping in liquid air. These preparations required usually about twenty minutes. Within that time all the Radium A on the wire had practically decayed and the whole α-radiation was due to Radium C only. The microscope was now adjusted on the line of scintillations and its position read. After exciting the magnetic field the microscope was again adjusted on the deflected line and its position again read. The adjustment and reading of the scale were repeated, and, if found to be in accordance with the previous reading, the magnetic field was changed and measurements again made in the same way. One set of these measurements could be taken within about twenty minutes. The activity after that time was still strong enough to allow another set of readings to be made. The air was admitted and the slide taken out. A sheet of mica of known stopping power was then placed immediately in front of the wire. After replacing the slide and re-exhausting the apparatus, measurement could be taken as before.

The actual deflections due to the magnetic field were of the order of 1 cm., the intensity of the field produced by an exciting current of 20 amperes being about 10,000 Gauss. The following Table I indicates the general course of procedure in an experiment:—

Table I.

Exciting current (amps.)	4.	8.	12.	20.
Actual deflections (mm.) without mica	5·82	8·12	9·17	10·43
Actual deflections (mm.) with mica equivalent to 0·90 cm.	6·14	8·51	9·61	10·89
Velocity of α-particles after passing through mica (initial velocity = 1)	0·948	0·952	0·954	0·959
Average	0·953			

The results which were obtained for different thicknesses of mica are collected in the following table:—

Table II.

Equivalent thickness of mica sheets in cm. of air.	Intensity of exciting current in amps.								Average relative velocity.
	0·5.	1·5.	2·5.	3·5.	4.	8.	12.	20.	
	Relative velocity (velocity of expulsion = 1).								
cm.									
0·90	—	—	—	—	0·948	0·952	0·954	0·959	0·953
1·98	—	—	—	—	0·875	0·888	0·887	0·895	0·886
3·00	—	—	0·828	—	0·804	0·827	0·807	0·823	0·818
3·66	—	—	0·770	—	0·760	0·770	0·768	—	0·767
4·79	—	0·668	0·695	0·682	0·682	0·684	—	—	0·681
5·81	0·548	0·548	0·555	0·552	—	—	—	—	0·551
6·08	0·488	0·475	0·492	0·507	—	—	—	—	0·49
6·57	0·394	0·396	—	—	—	—	—	—	0·39
6·80	0·27	—	—	—	—	—	—	—	0·27

The first column gives the stopping power of the mica sheets expressed in centimetres of air under standard conditions, the determination being made by the scintillation method. The last two absorbing screens, equivalent to 6·57 and 6·80 cm. of air, were obtained by adding to a sheet of mica, equivalent to 6·08 cm., 15 and 21 gold foils respectively. Each of these gold foils corresponded to 0·034 cm. of air.

It was not possible to measure the magnetic deflection of the α-particles which had passed through an equivalent thickness of 6·8 cm. of air for a stronger field than that excited by 0·5 ampere (equal to 950 Gauss). The scintillations produced by the α-particles after passing through this thickness were extremely weak and at the limit of visibility. In addition, their number was much diminished, and they were spread out over a much greater area than usual, this being probably due to variations in velocity produced by scattering.

The average actual deflection obtained in this case for an exciting current of 0·5 ampere was 3·1 mm., which corresponded to a velocity of 0·27 of the velocity of expulsion. The agreement in different readings made by two observers was such that the error in this figure will hardly exceed 10 per cent. In all the other experiments where the velocity of the α-particles was high the scintillations were easy to observe, and the probable error in these cases is not more than 1 per cent. The error in the determination of the thickness of the mica sheets amounted to about 2 per cent.

The average values obtained for the velocities are plotted against the range in fig. 2. It will be seen that the velocities v found at different distances x from the source agree well with the equation

$$v^3 = a(\mathrm{R}-x).$$

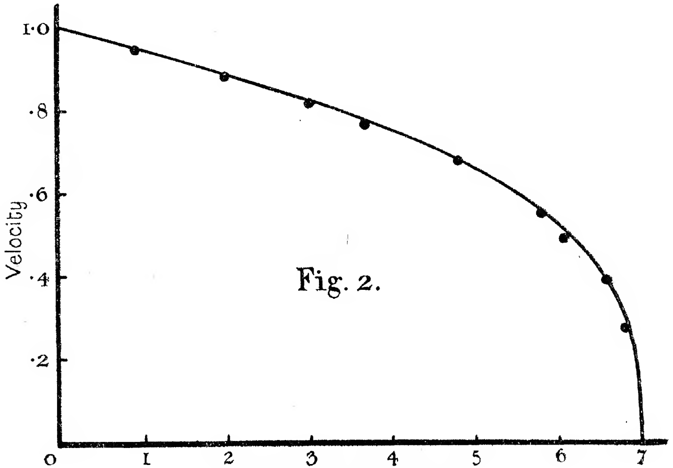

Fig. 2.

The best agreement was obtained taking the constant R equal to 7, which is very nearly equivalent to the maximum range of the α-particles from Radium C in air. Since for $x = 0$ the velocity of the α-particle is assumed to be unity, the factor a becomes 0·143.

We may therefore conclude that the velocity of an α-particle, at any point of its path, is proportional to the cube root of the range it has still to run. It will also be seen that towards the end of the range the velocity of the α-particles decreases rapidly, and probably becomes so small there that it is comparable with that of the gas molecules. The α-particle will then behave like an ordinary gaseous ion.

The velocity curve obtained by Prof. Rutherford is, for the first 6 cm. of the range, in good agreement with the curve above. This will be seen from the following table:—

Table III.

Range.	Velocity.	
	Rutherford.	Geiger.
cm.		
1	0·95	0·95
2	0·87	0·89
3	0·80	0·82
4	0·75	0·75
5	0·65	0·66
6	0·52	0·52
7	0·43	<0·2

It seems probable that the difference at the end of the range is due to the use of aluminium sheets in the photographic experiments of Prof. Rutherford. These aluminium sheets are never quite uniform in thickness, and a certain fraction of the α-particles will, after passing through them, still have a velocity somewhat higher than the average. But these swifter particles are most effective on the photographic plate, and in consequence of this the deflection will appear too small.

II. *The Distribution of Velocity in a Parallel Pencil of α-Rays.*

The ionisation which is produced by a parallel pencil of α-rays starting with identical velocity is given by the curve (fig. 3) of the first paper (*loc. cit.*). It is not essential that this curve also represents the ionisation due to the absorption of a single α-particle. For even if all Ra C α-particles are actually expelled with identical velocities from their parent atoms, they will acquire, in the course of their passage through the air, a small difference in velocity. This difference will be due partly to a variation in the number of collisions with the gas molecules, partly to the scattering of the α-particles in their passage through the gas. It will be shown by the author in another paper that the amount of scattering, although small for α-particles of high velocities, increases rapidly towards the end of the path.* It is therefore to be expected that the α-particles will show a small variation in velocity at the end of their range, and that the velocities will be distributed about an average value. In consequence of this, the ionisation curve, as measured for a pencil of α-rays, will be somewhat different from that obtained for a single α-particle.

From the experiments of Bragg and others† it is known that the number of α-particles remains constant when they pass through matter. This has recently been proved directly by Regener,‡ who found that the number of scintillations produced by the α-particles from a polonium disc remained practically unchanged when the disc was covered with aluminium foils. But the number decreased rapidly when the thickness of aluminium was nearly equivalent to the range of the polonium particles.

In the following experiment the decrease of the number of scintillations near the end of the range is studied in more detail. The α-particles from a narrow source of Radium C were allowed to fall on a zinc sulphide screen, which was fixed to a microscope suitable for counting scintillations. The distance between the source of α-rays and the screen could be varied. The number of scintillations was counted within the last centimetre of the range at intervals of 1 mm. After correcting for the decay and the change of distance, a curve was obtained connecting the range with the number of scintillations observed per minute.

The curve is shown in fig. 3. It appears that the number of scintillations begins to decrease noticeably at about 6·4 cm. from the source. At a point slightly above 7 cm. practically no scintillations could be observed. We may therefore conclude that towards the end of the path the velocity is not the same for all α-particles, some of them being able to travel several millimetres further than others.

A similar result was obtained by using polonium as a source of rays. In this case the observations could be made with greater accuracy on account of the constancy of the source.

The same conclusion as above may be drawn from the experiments of

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* Preliminary account, 'Roy. Soc. Proc.,' A, vol. 82, p. 174, 1908.

† H. W. Bragg, 'Phil. Mag.,' vol. 10, p. 318, 1905; E. Meyer, 'Phys. Zeits.,' vol. 7, p. 917, 1906.

‡ Regener, 'Verhdlgn. d. D. Phys. Ges.,' vol. 10, p. 78, 1908.

E. Aschkinass,* who measured the charge carried by the α-particles from polonium at different parts of their range.

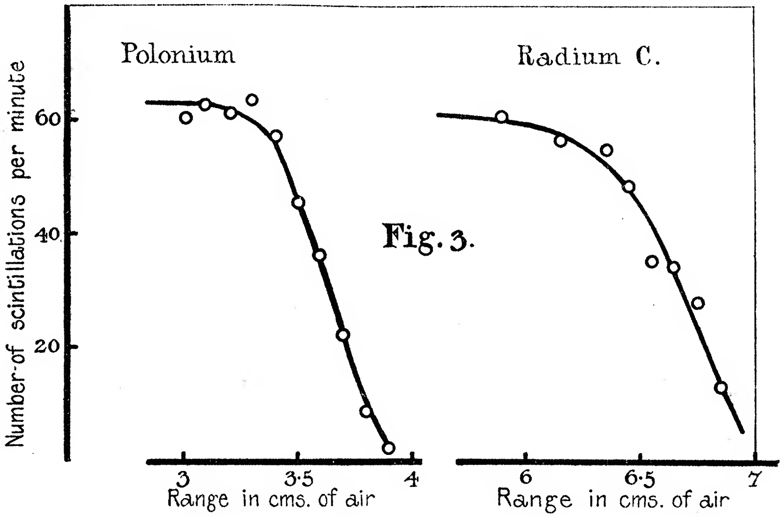

Fig. 3.

It might be suggested that the difference in velocity at the end of the path could be ascribed to a slight variation in the speed with which the α-particles are initially expelled. However, from the sharpness of the photographic image of a deflected pencil of α-rays, Prof. Rutherford concluded that the α-particles from Radium C are all expelled with the same speed.

The variation in velocity, however, which might be expected from the behaviour of the α-particles at the end of the range would be of the order of only 5 per cent., a quantity which might escape detection unless the pencil of α-rays suffers a large deviation.

It appeared, therefore, of interest to test whether by a more delicate method a variation in the velocity of expulsion might be detected. The arrangement was similar to that shown in fig. 1, except that the metal case extended about 10 cm. beyond the magnetic field, so that the distance from the active wire to the zinc sulphide screen was increased to 24 cm. In consequence of the great distance the image of the slit on the screen had a measurable width. This width was carefully measured by means of the microscope in a similar way to that described above. After exciting the field, the image was shifted several centimetres. The width of the band of the scintillations was again measured in the deflected position. The following table shows the results:—

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* 'Ann. d. Physik,' vol. 27, p. 377, 1908.

Table IV.

Exciting current.	Intensity of magnetic field.	Actual deflections.	Width of image.
Amps.	Gauss.	mm.	mm.
0	—	—	0·55
4	6700	19·6	0·50
10	9900	27·8	0·49
20	12000	33·9	0·52
0	—	—	0·50

The figures in the last column represent the average values of several observations. They are constant within the limits of experimental error. A change in the width of the image of 30 per cent. (= 0·15 mm.) would have been recognised with certainty. Since the actual deflection was of the order of 30 mm., we may conclude that the variation, if any, in the initial speed of the α-particles fron Radium C is certainly less than 0·5 per cent.

Thus, according to the above experiments the α-particles from Radium C are all expelled from their parent atoms with the same initial speed, but they acquire in passing through matter a slight difference in range of the order of 5 mm. As a rule the range of an α-particle from Radium C is given as 7·06 cm. of air. This coincides with the extreme end of the ionisation curve, as well as that of the scintillation curve. Since only a small portion of the α-particles actually travel as far as 7 cm., the average range of an α-particle expelled from Radium C will be appreciably less, namely, about 6·7 cm.

III. *Relation between the Ionisation produced by the α-Particles and their Retardation by Matter.*

It has been shown previously that at a distance x from the source the velocity v of an α-particle passing through air can be represented very closely by the equation

$$v^3 = a(\mathrm{R}-x), \qquad (1)$$

where a and R are constants, R denoting the maximum range of the α-particle. In comparing this equation with the experimental results, R was taken as 7, which expresses that velocity becomes zero after the α-particle has passed through 7 cm. of air. It was shown, however, in Section II that only a small portion of the α-particles travels as far as 7 cm., about half of them being already absorbed after passing through 6·7 cm. It will be clear from the manner in which the measurements of the velocity were made that the curve, fig. 2, does not apply for an average α-particle, but rather expresses the change of velocity of an α-particle which happens to travel through the whole range. It will, however, be legitimate to assume that the velocity curve of an α-particle of average range (6·7 cm.) is given by the same equation, if for R the value 6·7 is used.

The most probable and natural assumption is that the ionisation produced by an α-particle in a given thickness of matter is proportional to the energy absorbed. Under this assumption the ionisation I produced at any part of the path may be calculated from the above equation for the velocity. We obtain

$$I = b\frac{d(v^2)}{dx} = c(R-x)^{-\frac{1}{3}},$$

or

$$I^3 = \frac{a'}{R-x}. \qquad (2)$$

This theoretical ionisation curve is drawn in fig. 4 in full, R being taken equal to 6·7. The curve represents therefore the ionisation produced by a single α-particle with average range. According to this curve the ionisation produced by a single α-particle, would increase rapidly towards the end of the range and then fall suddenly to zero. This appears quite probable, since we know that the positive particles in discharge tubes (Kanal-rays) are highly effective in ionising, although they travel at comparatively very low velocities.

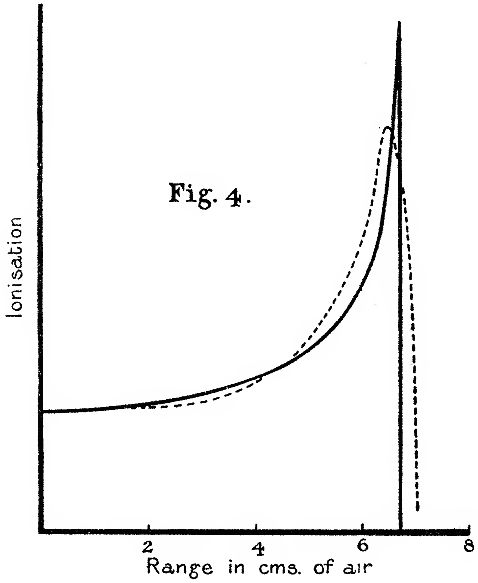

Fig. 4.

The curve for a *pencil* of α-rays will obviously be somewhat different to the curve for a *single* particle. For it will be built up of a great number of similar curves grouped about the curve of average range. It is clear that the resulting curve will show a very similar rise, but while the ionisation of a single particle will show a rapid increase and then a sudden stoppage, the curve for a pencil of α-rays will pass gradually through a smooth maximum value and from there fall to zero in a fairly steep line. As a whole the resulting curve will be in fair agreement with the ionisation curve found experimentally, which is plotted with a dotted line for comparison in the same diagram.

It is therefore to be concluded that along the whole path of an α-particle the ionisation produced by it is proportional to the rate at which it loses energy.

Combining equations (1) and (2), we obtain

$$I \times v = \text{const},$$

i.e. the ionisation or expenditure of energy is inversely proportional to the velocity, or in other words, the ionisation produced at any point of the path is proportional to the time which the α-particle takes to cross the atom. If we assume this law and the proportionality between ionisation and expenditure of energy, then the velocity curve $\{v^3 = a\,(R-x)\}$ and the ionisation curve $\left[I^3 = \frac{a'}{R-x}\right]$, which have both found experimental verification, would follow by deduction.

It is of interest to note that Prof. Bragg,* although starting from different equations, arrived at the same conclusion, namely, that the ionisation produced by an α-particle is inversely proportional to its velocity. The data, however, which were available at that time as regards the velocity, were against a proportionality between ionisation and expenditure of energy.

IV. *Conclusions.*

(1) The velocity of an α-particle expelled from Radium C decreases rapidly towards the end of its path.

(2) The velocity with which the α-particles are expelled from the Radium C atoms is constant within the experimental error of 0·5 per cent. In passing through air, the α-particles acquire a slight difference in velocity.

(3) The ionisation produced by an α-particle is at any point of its path proportional to the rate at which it loses its energy.

(4) The loss of energy is inversely proportional to the velocity.

I wish to acknowledge the assistance which Mr. E. Marsden, B.Sc., has again given me in many of these observations; and I desire to express my sincere thanks to Prof. Rutherford for his kind interest and help during the progress of this research.

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* 'Phil. Mag.,' vol. 13, p. 350, 1907.

Additional Note.—Some very interesting experiments on the retardation of α-particles by metals and gases have recently been published by T. S. Taylor.* He has shown that the stopping power of metal foils decreases with decreasing speed of the α-particles entering them, and that the rate of decrease is approximately proportional to the square root of the atomic weight of the metal used. Taylor also determined the Bragg ionisation curves in air and hydrogen, and found a slight difference in their shape This difference, in connection with the other results, indicated that the large ionisation near the end of the range of an α-particle is due, at least in part, to the fact that the particle loses its energy more rapidly in this part of the range. This conclusion is in agreement with the experiments described in the foregoing paper, which made it highly probable that ionisation produced and energy spent by an α-particle, in passing through matter, are proportional.

In the light of the experiments of Taylor, it appears objectionable to use hydrogen in the ionisation vessel which served in my previous experiments to measure the ionisation produced at different points of the path, the previous absorption of the α-particles being made in air.† The more rapid increase of the ionisation towards the end of the range which was observed when the ionisation vessel was filled with hydrogen than when it was filled with air, is perhaps not, as it was supposed, due to the more complete saturation obtained in that gas, but is due to a small change in the relative number of ions produced along the path of the α-particles in air and hydrogen. In consequence of this, the whole number of ions produced by the α-particles from the different radium products, as calculated from the ionisation curve, and given in Table III of the previous paper (*loc. cit.*), would be slightly too great by an additive constant.

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* 'Phil. Mag.,' vol. 18, p. 604, 1909.

† See fig. 2 of previous paper, 'Roy. Soc. Proc.,' A, vol. 82, p. 486, 1909.